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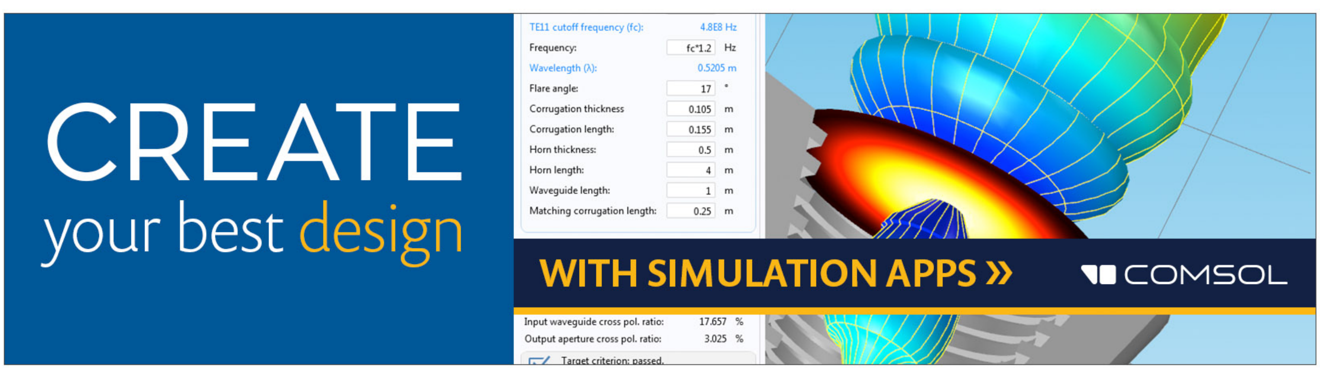

Parity effect in Al and Nb single electron transistors in a tunable environment

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Two different types of Cooper pair transistors, with Al and Nb islands, have been investigated in a tunable electromagnetic environment. The device with an Al island demonstrates gate charge modulation with 2*e* periodicity in a wide range of environmental impedances at bath temperatures below 340 mK. Contrary to the results of the Al sample, the authors were not able to detect 2*e* periodicity under any conditions on similar samples with Nb island. The authors attribute this to the material properties of Nb. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2768897]

A Cooper pair transistor (CPT) is a basic element for a number of applications such as ultrasensitive electrometry, quantum computing, and metrology. Until now, Al, with superior characteristics of Al oxide as the tunnel barrier, has been the material of choice for a CPT. Yet, due to its higher superconducting gap Δ as compared to that of Al, Nb would be an interesting alternative for superconducting devices. Larger Δ ensures a wider range of operation in terms of the working temperature and tolerance to external noise. Moreover, the operation speed is typically proportional to the value of Δ.

A major, still largely unexplained, disadvantage in employing CPT based devices is their susceptibility to quasiparticle poisoning. Ideally, only paired electrons contribute to the charge transport in CPTs and the island parity remains preserved, resulting in 2*e* periodicity of the CPT transport. However, in a real experiment single electron, or quasiparticle, tunneling may change the parity and transport periodicity. This is the effect usually referred to as quasiparticle poisoning. In Al based devices quasiparticle poisoning can be suppressed in many cases,[1–5] but there are no reports on quasiparticle-free CPTs made of Nb, although a wealth of experiments already exist on these systems.[6–11] This is surprising to some extent because larger Δ should, in principle, diminish quasiparticle poisoning. Moreover, in the case of CPT with Al leads and a Nb island, the larger superconducting gap of the island should further suppress quasiparticle tunneling into the island.[2–4] The question remains whether the quasiparticle poisoning in Nb structures is due to their susceptibility to environment fluctuations, or whether it is an intrinsic material property of Nb. The aim of the present work is to investigate the parity effect under identical experimental conditions in CPTs with Al leads but with either Al or Nb island. We also employ the recently developed concept of tunable environment,[5,12] which should significantly suppress quasiparticle poisoning.[5]

The measured CPTs consist of a superconducting island (Al or Nb) coupled to two superconducting Al leads via nominally identical Josephson junctions and capacitively coupled to a gate electrode [Fig. 1(a)]. The samples are fabricated by two-angle evaporation through a suspended Ge mask supported by a thermally stable polymer.[13] In both cases the first evaporated layer is Al and the tunnel barrier is formed by thermal oxidation of Al. The CPT island (15 nm thick Al or 30 nm thick Nb) with dimensions of 460×130 nm^2 is connected to two Al leads (25 or 15 nm thick) by two tunnel junctions whose dimensions were slightly varied around 100×100 nm^2 giving the charging energy of the devices, $E_c = e^2/(2C_\Sigma)$, of about 100 μeV, C_Σ being the total capacitance of the island. Close to the CPT island, each of the two Al leads is split into two 22 μm long superconducting quantum interference device (SQUID) arrays consisting of 81 SQUIDs each.

The measurements are performed in a ^{3}He/^{4}He dilution refrigerator in a four-probe configuration for CPTs and using only two probes for SQUID arrays. All measurement lines were filtered using 1.5 m of thermocoax between 1 K plate and the sample stage and a low pass filter on the sample stage. SQUID arrays serve as additional filters and allow us to modify environmental impedance of the CPT by variation of a perpendicular external magnetic field. The parameters of

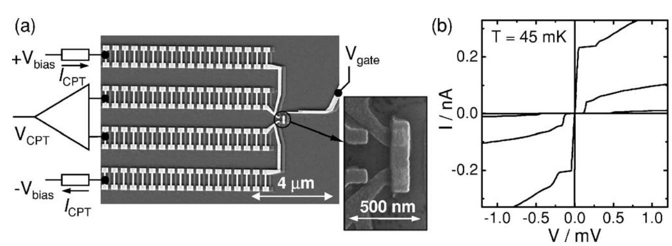

FIG. 1. (a) Electron micrograph of a CPT with SQUID arrays and diagram of measurement circuit (left) and an enlarged image of the CPT island (right). (b) Current-voltage characteristics of two SQUID arrays around zero bias in sample Al-6 at T=45 mK for values of magnetic flux from zero to half flux quantum through each SQUID. Zero bias resistance of the arrays varies from 7 kΩ up to 5 GΩ in this case.

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TABLE I. Parameters of the measured CPTs.

Sample	Nb-1	Nb-4	Nb-7	Al-6
Island	Nb	Nb	Nb	Al
$2R_N$ (kΩ)	24	183	112	63.2
E_J (μeV)	116	15	25	21
E_C (μeV)	112	83	183	118
$R_0^{\min}$ (kΩ)	0.45	0.9	1.0	7
$R_0^{\max}$ (GΩ)	0.75	2.1	11	5

the investigated samples are listed in Table I. The charging energy of the transistor was derived based on Coulomb blockade at a temperature above the critical temperature of both superconductors. The measured values of the charging energy are in agreement with the charging energy derived from the size of the junctions. Josephson coupling energy E_J for one CPT junction is derived from the normal state resistance of the junction R_N assuming $\Delta_{\mathrm{Al}} \simeq 0.2$ meV and $\Delta_{\mathrm{Nb}} \simeq 1$ meV.

We characterize the environment simply by their zero bias resistance R_0 bearing in mind that the real impedance may be different. R_0 is obtained from the current-voltage (*IV*) characteristics of the arrays. As an example, *IV* characteristics of two arrays in series for sample Al-6 measured at different values of the magnetic field threading the SQUID loops are shown in Fig. 1(b). The applied magnetic field suppresses supercurrent of the SQUIDs, which leads to increase of the zero bias resistance. At higher magnetic fields, Coulomb blockade becomes pronounced and develops in a wider voltage range. Maximum and minimum values of R_0 at 50 mK of two SQUID arrays connected in series are given in Table I. The minimum R_0 and its dynamic range vary from sample to sample, and this can be ascribed to different values of critical currents from sample to sample and to the spread in SQUID parameters. In the Al/Nb hybrid samples the SQUID junctions are formed between two different superconductors, which also affects their characteristics. Nevertheless, it was possible to tune R_0 over almost six orders of magnitude in all the samples.

The CPT is biased through the SQUID arrays which means that the *IV* characteristics and gate modulation are measured in the current biased regime. General features of the measured all-aluminum sample (Al-6) are in agreement with the theoretical predictions for a CPT.[5,14–16] At a high enough environmental impedance, Coulomb blockade of Cooper pair tunneling develops. At $R_0 > 10\ M\Omega$ *IV* characteristics demonstrate back bending (not shown), which is a manifestation of Bloch oscillations. At $R_0 < 10\ M\Omega$ the gate modulation of *IV* characteristics is $2e$ periodic at the bias points corresponding to the supercurrent branch and e periodic at higher current values [Fig. 2(a)]. At low voltage (supercurrent branch) the modulation period is 42 mV, which is twice larger than that at higher voltages. The smaller period coincides with that observed in the same CPT in the normal state (at high temperature or in high magnetic field), which confirms that the observed reduction of modulation period corresponds to the $2e$-e transition. In our case, $2e$ periodicity could be observed in the Al sample at all values of the environmental impedance, unlike in the experiments reported earlier.[5,17] Corlevi *et al.*[5] observed transitions from e to $2e$ only at rather high values of R_0 (>5 MΩ) using a similar Al CPT. This may reflect a difference in the impedance seen by

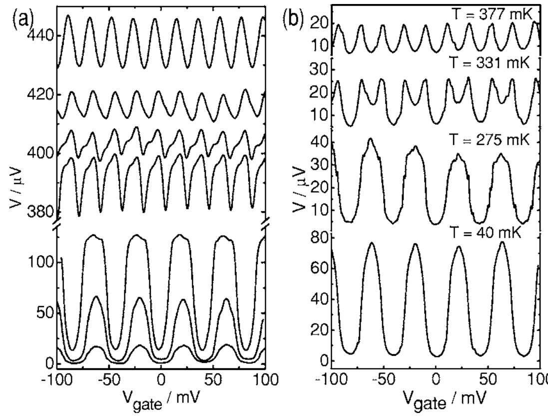

FIG. 2. Gate induced CPT voltage modulation of Al-6 sample at $R_0 = 7$ kΩ (a) at different bias currents at $T = 40$ mK and (b) at different bath temperatures.

the CPT for the same value of R_0 due to the different layouts in our experiment and in Ref. 5 or filtering of the signal lines. This is consistent with the relatively high effective noise temperature (150 mK) reported in Ref. 5. Also, the energy profile in our Al CPT (15 nm thick island and 25 nm thick leads) may be favorable for the observation of $2e$ periodicity.[3] Our results for high impedance regime (*IV* characteristics with negative slope) are similar to those in Ref. 5: $2e$ modulation was observed in the Bloch regime at low bias currents and e periodicity in the Zener tunneling regime. Gate modulation of sample Al-6 at different bath temperatures and at low array impedance of $R_0 = 7$ kΩ is presented in Fig. 2(b). Increase of temperature leads to increased concentration of thermal quasiparticles and as a consequence to a $2e \to e$ transition. Crossover temperature T^* for Al-6 sample is about 340 mK, which agrees with the theoretical prediction $T^* = \Delta / [k_B \ln(N_{\mathrm{eff}})]$,[18] where N_{eff} is the number of quasiparticle states on the island available for thermal excitation.

Three Nb samples with different E_J/E_C ratios were measured (see Table I). The parameters and measured characteristics of sample Nb-4 are rather similar to those of sample Al-6 described above. Samples with larger (Nb-1) and lower (Nb-7) E_J/E_C ratios were also investigated. All samples were measured over a wide range of environmental impedances and biasing currents. Like in the Al sample, the Coulomb blockade of the hybrid samples becomes more pronounced for higher environmental impedance. Gate modulation is, however, significantly weaker in all the Nb samples as compared to that in Al-6. Figure 3 gives a comparison of the gate modulation curves for Al-6 (a) and Nb-4 (b) samples at $T = 40$ mK. They were recorded in the supercurrent branch of the CPT and at different values of R_0 of the arrays. Initially, as expected, the voltage amplitude in the gate modulation increases with R_0, and then it drops in the back-bending regime of the CPT. Under all experimental conditions the period of gate induced modulation in the Nb samples, including the normal state, is about 20 mV, which is about the same as the e period of sample Al-6. We thus conclude that all our samples with Nb island exhibit only e-periodic modulation. To explain this, one should address material properties of Nb.[19] We believe the observed strong quasiparticle poisoning and a large subgap leakage in either Al/Nb or Nb/Nb junctions, as compared to all-Al junctions, have the same origin. With the angle evaporation technique, below 100 mK, we obtain the ratio of the subgap resistance to the normal state

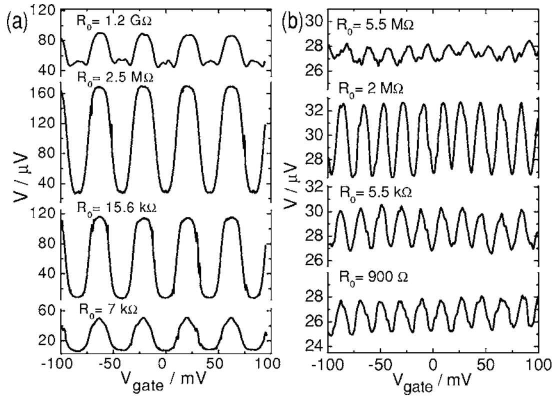

FIG. 3. Gate induced CPT voltage modulation of (a) sample Al-6 and (b) Nb-4 at different magnetic fields and at $T=40$ mK. Biasing point for both samples corresponds to supercurrent branch of *IV* characteristics. Zero bias resistance of the SQUID arrays is marked on the curves.

resistance for all-Al junctions of the order of 1000 while it is only about 50 for all-Nb junctions with a Nb oxide barrier.[20] In the case of the hybrid structures studied in this work, the ratio is equal to 200, similar to that measured in trilayer Josephson junctions. The reason for the quasiparticle poisoning can be the presence of quasiparticle states in the gap of Nb. As a strong gettering material, Nb may react with the chemical residues on the substrate and/or gas impurities inside the vacuum chamber during the deposition process, and this can result in creation of subgap states. Also, the quality of the Al oxide tunnel barrier may degrade during the deposition of the top Nb layer, leading to the formation of a complex interface containing lower Nb oxides between the Al/AlO_x and Nb layers and eventually to the quasiparticle leakage in the junction. Besides Nb island nonidealities, the presence of Nb in the leads may be an extra source of quasiparticles contributing to the poisoning in the hybrid structures.

In conclusion, we have presented a comparative study of the Cooper pair transistors made with either an Al or Nb island, embedded in tunable electromagnetic environments. The device with an Al island demonstrates gate charge modulation with clear $2e$ periodicity in a wide range of environmental impedances as long as the bath temperature is kept below 340 mK. This suggests that the Al sample is of good quality and the filtering of the measurement setup is sufficient to avoid quasiparticle poisoning. Contrary to the Al sample, the three similar samples with a Nb island measured in the same setup exhibit only e periodicity under all experimental conditions. Based on our observations, we attribute the absence of $2e$ periodicity in the CPTs with Nb islands to the material properties of Nb. Thus the suitability of Nb as the material for single Cooper pair devices still remains an issue.

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